Sustainable Retrofitting of Urban Streets for Mitigation of Traffic Vibration by Means of Anti-vibrating Trenches

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Abstract. Vibrations induced by vehicular traffic are of increasing concern in urban areas, especially because of nuisance issues perceived by inhabitants and possible damage problems experienced by exposed heritage buildings. Among the several countermeasures aiming at reducing the level of vibration at source or at mitigating the propagation of ground-borne vibration through pavement layers and underlying soils, the use of anti-vibrating trenches may offer an interesting solution in mitigating the vibrations caused by heavy vehicle traffic. In this paper, an original vibration prediction numerical model is developed and proposed that may help in the design procedure of such countermeasures. Following an initial calibration of the numerical model and a validation with experimental results derived by technical literature, preliminary findings obtained by making use of different materials and complex trench layouts are briefly presented and reviewed. It is acknowledged that an evaluation in frequency domain may offer an effective tool to retrofit existing urban road exposed to this issue.

Keywords: Road traffic induced vibration · Ground-borne vibration · Anti-vibration trenches

1 Introduction

The environmental impact of transport infrastructures represents a critical issue, especially in urban areas [1–4, 31]. Among different vehicular impacts (noise, air pollution, etc.) vibrations induced by road traffic have recently gained wider attention. It is worth to notice that traffic vibrations may be divided into two main types: air-borne and ground-borne vibrations. These latter are characterized by lower frequency content (0–20 Hz) and are produced by dynamic overloads transmitted to the pavement surface by heavy vehicles. Therefore, ground-borne vibrations propagating through road superstructure and underlying soils up to the foundation level finally reach the structural elements of the buildings close to the street. These type of vibrations are often claimed to be responsible for severe nuisance to building occupants and for minor structural damage in historical buildings [1, 5].

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The problem is usually divided into three main phases: a generation phase due to the dynamic interaction between vehicle and the roughness of road profile, a propagation phase of vibrations through the road superstructure and, subsequently, through the underlying soils up to the foundations and to the structures of adjacent buildings and, finally, a reception phase regarding the sensitivity of building occupants and dynamic response of building elements.

The study of the problem seems to be extremely complex: the generation phase implies knowledge of mechanical engineering as far as the vehicle model is concerned, whereas the highway engineering expertise is required for road profile representation; furthermore, the propagation phase implies knowledge of geotechnical engineering, as far as dynamic behavior of soils is concerned, and, finally in the reception phase, structural dynamics is the main topic involved. For these reasons, there are few studies in the literature where the problem has been addressed as a whole. Up to now, the approach followed in order to tackle the problem has often been mainly experimental or theoretical.

An in-depth experimental study [6–9] on ground-borne traffic induced vibrations has been carried out at Transport and Road Research Laboratory, (now Transport Research Laboratory, TRL) in UK within the past thirty years. It has been observed that a strong link exists between heavy vehicle traffic, vehicle speed and height of localized surface irregularities (humps). In Italy, few experiments have been recently conducted on traffic induced vibrations and most of them were aimed at evaluating possible damaging effects for heritage buildings [1, 5, 10].

Prediction models for traffic vibration level, can be broadly divided into two groups: empirical and semi-empirical ones, on one hand, and analytical and numerical ones, on the other. Among the former ones, the most noticeable appears to be that developed by TRL, where an estimate of the vertical Peak Particle Velocity (PPV) vibration induced at the foundation level when an heavy vehicle is moving over a localized unevenness is proposed. The formula takes into account the maximum height or depth of a singular surface irregularity (hump) over which the heavy vehicle transits, the speed of the vehicle, the type of road surface, soil properties and the distance between the unevenness and the building foundation [11, 12]. This model has been modified in order to take into account longitudinally distributed road surface irregularity [1].

Empirical and semi-empirical models, due to their simplifying assumptions, cannot take into consideration all the factors involved in the phenomenon, therefore more refined analytical and numerical prediction models have been developed. An analytical model that allows to evaluate the vertical vibration level (vertical displacement, velocity or acceleration) in terms of Power Spectral Density (PSD) function, at an arbitrary distance from the road has proposed by H. M. Hunt [13]. Different authors have developed prediction models employing a Finite Element Method (FEM) approach in order to study the propagation through the road pavement and through underlying soils [14]. It is also worth to mention a recent analytical model developed by Lombaert et al. [15] that allows to evaluate the vibration level, expressed in terms of PSD or frequency spectrum, produced by an half-car model that is interacting with a stochastic (PSD) or a deterministic road profile, and is moving on a visco-elastic layered medium.

1.1 Vibration Mitigation Countermeasures

Basing on the previous phenomenological description, several countermeasures aimed at mitigating the vibration can be employed and accordingly grouped:

- *generation related countermeasures* where factors affecting the dynamic interaction between vehicle and pavement are addressed; typical example of such measures are traffic restrictions (as far as heavy vehicles and limit travel speed are concerned) or pavement surface smoothing (by improving maintenance by means of frequent resurfacing and re-shaping interventions);
- *propagation related countermeasures* where vibration waves are usually intercepted at pavement level or in the underlying soils or finally at building foundation level; in this case feasible solutions may be anti-vibrating pavement, anti-vibrating trenches or building base isolation respectively.

As regards this latter family of measures, anti-vibrating pavements may represent an effective solution to mitigate the vibration level [16] but, on the other hand, they appear more invasive and time-consuming if traffic disruptions related to roadworks are concerned. Building base isolation is a well-known solution derived from earthquake engineering but it is rather expensive and therefore cannot be systematically implemented along a continuous building façade facing the road. In this connection, the use of anti-vibrating trenches may offer a more feasible and somehow affordable solution to tackle the problem.

As a matter of fact, the use of trenches for vibration screening has been the subject of several research efforts in the past fifty years. Most relevant pioneering work has been presented by Barkan and by Woods that evaluated the effectiveness of some trench lay-out by means of an experimental campaign with surface harmonic vibration source [17, 18]. Later on, Haupt presented major contributions by means of an extensive numerical sensitity analysis by a FEM approach thus providing a more comprehensive theoretical background for the operational aspects of these kind of trenches [19, 20]. More recently, several remarkable works employing a combined 2D FEM-BEM (Boundary Element Method) approach [21–23] has provided more insight in the behavior of open or filled trenches whereas the recent use of geofoam polyurethane based products as filling material has been investigated and appears promising [24–27].

However, it seems that till now no enough effort has been devoted in analyzing the performance of finite trenches or in evaluating the effectiveness of more complex geometric layouts other than a continuous plane screen or pile walls.

To this purpose, following a preliminary calibration and experimental validation an innovative 3D FEM model has been developed in order to evaluate mitigation performance of this latter trench layout in near-field conditions typically encountered in a urban environment.

The novelty of the proposed approach lies in:

- the use of a simple FEM model to simulate the vibration propagation in the near field conditions instead of an hybrid BEM-FEM approach that is not so widespread diffused in the technical community;
- the numerical validation of the FEM model with closed-form analytical solutions that can guarantee a better mathematical reliability of the proposed modeling approach

- the experimental validation of the FEM model with field data collected on different soils and derived from scientific literature;
- the ability to implement complex trench layout that could be designed in a tailoring way for the specific intervention site.

2 Modelling Vibration Propagation

2.1 Basic Assumptions

As far as the modeling of traffic induced vibrations is concerned, an important assumption that has been widely accepted is that the dynamic coupling between vehicle and road superstructures can be neglected, since mass and stiffness of pavement involved in the vibration phenomenon are much larger than those pertaining the heavy vehicles. Therefore, the problem can be split into two steps: 1) evaluation of dynamic overloads and 2) application of dynamic forces to the pavement surface. Accordingly, the prediction model is divided into two sub-models described in the followings.

Vibrations originated by dynamics loads propagate through the various pavement layers and to subgrade soils and finally reach the foundations of the sensitive structures close to the road. In order to mathematically simulate the phenomenon, the dynamic response (in terms of displacement, velocity or acceleration) for a point located at a defined distance from a vertical pulsating force acting on the surface of a medium (within which the phenomenon can still be considered relevant) has to be evaluated.

When the geometrical layout of this medium is not complex, such as for simple or multi-layered half-space, approximated analytical solutions are available [13, 28]. When finite pavement cross-sections or trenches are present, the geometrical layout is more complex, and a Finite Element Method (FEM) approach has to be used.

2.2 FEM Propagation Model Description and Calibration

The development of a FEM model aimed at simulating vibration wave propagation, implies a major drawback that is related to the correct modeling of boundary conditions. Since the medium modeled is inherently finite, vibration waves impacting to boundary surfaces may be reflected and propagate back to the source. This may dramatically alter the dynamic response evaluated at a defined point, since in the real conditions, vibration waves are not reflected but propagate to the infinite and, moreover, they undergo to an attenuation due to the well-known "radiation damping" effect. In order to correctly simulate this aspect, very complex boundary conditions have been developed by several authors [14, 29] or Finite Element Method combined with Boundary Element Method approaches have been used [21–23].

In this study, the propagation phenomenon has been simulated by a transmission sub-model, that employs a FEM technique. The novel feature of this approach is that nor particular boundary conditions neither BEM elements have been used. This allows to virtually implement the propagation simulation on every commercially available general purpose FEM code. As a matter of fact, the vibration waves directed to the external surfaces of the finite medium are progressively attenuated within a damping zone [16, 30] that envelopes the whole finite medium. Material properties of the damping zone

are equal to those of the adjoining medium, except the damping coefficient. This latter varies according to a quadratic law with initial null tangent when going far away from the vibrating source.

In FEM models, the simulation of wave propagation in viscoelastic solids is usually tackled through a a step by step dynamic analysis. This procedure has proven to reproduce transient phenomena in the dynamic response more effectively than a natural frequency analysis performed by means of an Eigenvalue extraction. The equilibrium equations of a discretized model can be written in matrix form. In order to obtain the time history response of each node in the model a step by step integration in the time domain has to be performed. By assuming that equations of motion describing the problem are satisfied at discrete time points within the solution time interval and by postulating the variation of displacement, velocity and acceleration within the time increment, Δt, several direct integration schemes possessing different accuracy and stability properties have been proposed. Within the numerical simulation performed, an implicit direct integration scheme has been adopted since it can be demonstrated that this computational procedure is unconditionally stable with respect to the time increment value, Δt.

In order to verify the effectiveness of the FEM model in describing wave propagation phenomenon, a comparison has been made with results provided by an equivalent analytical solution. According to [13], within the frequency domain, the dynamic vertical displacement in far field conditions, at a defined distance from a vertical pulsating force acting on the surface of a viscoelastic half-space, can be synthetically expressed through the following expression:

$$H_z(r,\omega) = \left(\frac{\omega K}{2\rho\, c_R^3}\right) \cdot e^{\left(-\frac{D\omega^2 r}{2c_R}\right)} \cdot H_0^{(2)}\left(\frac{\omega\, r}{c_R}\right) \tag{1}$$

where r is the distance from the pulsating point force, ω is the circular frequency, K is a function that depends on Poisson's Ratio of the material, ρ is the material density, c_R is the velocity of Rayleigh surface waves, D is the damping coefficient, $H_0{}^{(2)}$ is the second type Hankel function of zero order.

As far as the FEM model by means of a General Purpose FEM Simulation Tool (LUSAS™) is concerned, an axisymmetric model has been developed and characteristic element dimension and therefore optimal mesh discretization can be derived when material properties (density and Young modulus) and maximum frequency of interest are known. As a matter of fact, if the relationship:

$$v = \lambda \cdot f \tag{2}$$

that ties wave velocity, v (that, for viscoelastic solids, depends only on material properties), with wavelength, λ , and frequency, f, is taken into account, by fixing the wave speed and the maximum frequency of interest, the minimum wavelength and thus the minimum element dimension (at least, equal to $\lambda/4$) is determined, in order to correctly simulate the wave propagation phenomenon. In the following figure, a comparison between the dynamic vertical displacement in the frequency domain provided by the expression (1) and those derived from numerical FEM model (the first one with uniform, not optimized, discretization and the second one with an optimized mesh) is presented. As it can be

easily observed, there seems to be a reasonable agreement between the analytical and the numerical FEM frequency response functions, even with a very low number of elements provided that a suitable mesh transition bands have been conveniently placed in the model in order to reduce the overall amount of elements (Fig. 1).

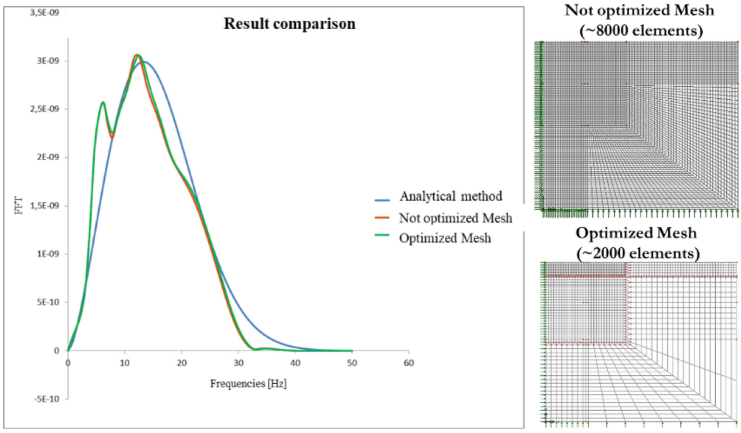


Fig. 1. Comparison in the frequency domain between the analytical and the numerical FEM dynamic response.

2.3 Experimental Validation of the Vibration Propagation Numerical Prediction Model

Following these results, an attempt to experimentally validate the simulation model with field data reported in an experimental study on traffic induced vibration carried out in UK [11, 12] has been performed. To this purpose, data on soil properties, on road superstructure and pulse loads by means of a Falling Weight Deflectometer (FWD, namely a Dyntest 8000 model with a peak loading of 60–70 KN and a sampling window of about 60 ms), have been collected and implemented in the simulation model.

Experimental frequency response functions (FRF) have been derived at various distance from the vertical pulse force. FRF Modulus of surface vertical vibration velocity measured at 12 Hz for increasing distance has been compared with that provided by FEM model where a visco-elastic material behaviour has been assumed. In detail, elastic behaviour is described by the Young Modulus and Poisson Ratio. Viscous behaviour has been taken into account by means of a Rayleigh damping parameters (stiffness and mass proportional) that have been calibrated in order to approximate the real damping properties (viscous, hysteretic or mixed) of the specific material examined [16, 30].

A sample of the results of comparison are conveniently reported in the following figure. As it can be seen, agreement between experimental and numerical dynamic response seems acceptable thus demonstrating the soundness of the FEM modelling developed (Fig. 2).

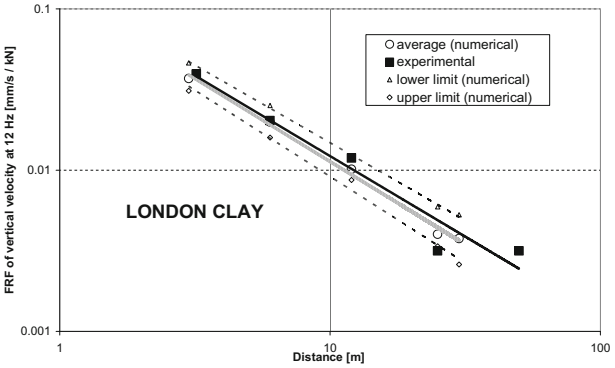


Fig. 2. Comparison between experimental and theoretical 12 Hz FRF for a FWD test performed on a London Clay soil in [11, 12] and compared in [30].

3 Analysis of Results

Basing on the aforementioned results, a new 3D numerical model has been developed in order to study the screening effectiveness of several type of trenches' layouts filled with geofoam.

The use of 3D modelling is related to the need of investigating different layouts (such as finite and infinite trenches or trenches with specific and complex shapes) and different relative positions for vibration source and for the receiver that cannot be accurately captured by a 2D modeling approach. However, it has to be acknowledged that a 3D propagation numerical model requires a dramatically higher computational effort.

Basing on these premises, an overall 20 x 20 x 20 m long study area was chosen to evaluate the trench mitigation effectiveness. As previously highlighted, the size of the study area is consistent with near-field behavior that it is intended to be investigated since in urban areas distance between the vibration source and the receiver is often very low.

Similarly to what carried out in the 2D modelling, a surrounding damping volume that is wrapping the study area has been conveniently considered in order to simulate far field restraining conditions. Furthermore, dual orthogonal symmetry conditions were exploited to represent a much wider area (as a matter of fact, the actual size of the FEM model corresponds to one fourth of the real investigated area). By making use of the calibration results obtained from the aforementioned axisymmetric propagation model, it was possible to reduce the overall amount of solid elements from nearly 180000 to about 55000, thus yielding a substantial reduction of computational time. In the following figures a general view of the 3D model and a plan view where the position of the vibration source and of several receiver points for a infinite (continuous) and finite trenches are reported (Figs. 3 and 4).

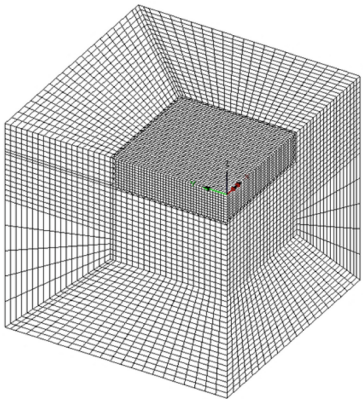


Fig. 3. A general view of the 3D FEM propagation model developed (nearly 55000 solids elements).

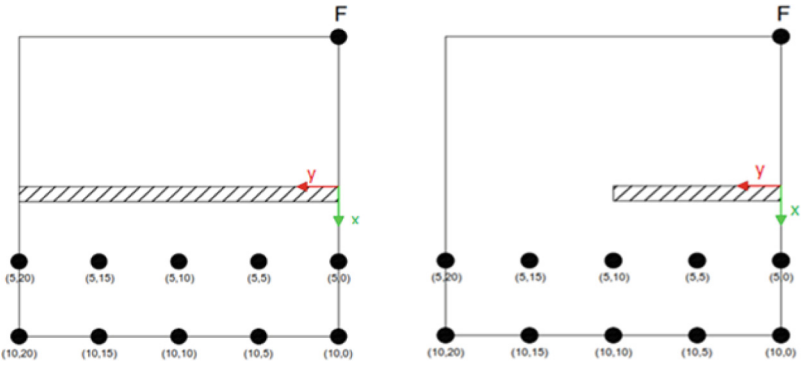


Fig. 4. A schematic plan view of the position of vibration source (point F), position and layout of trench and receiver's position for an infinite (on the left) and finite (on the right) trench.

3.1 Results from Numerical Simulations

By applying a pulse load, it was possible to obtain the frequency response function for a specific receiver located behind the trench. This information appears to be more useful if the screening effectiveness of a specific trench layout placed on a defined terrain throughout the frequency domain has to be investigated, especially if vehicular traffic ground-borne vibrations can be regarded as a narrow band frequency phenomenon.

In this regard, an attenuation parameter expressing the trench performance can be defined as:

$$Attenuation = \frac{Response\ in\ the\ frequency\ domain\ with\ trench}{Response\ in\ the\ frequency\ domain\ without\ trench} \tag{3}$$

As far as the numerical simulation are concerned, particle vibration vertical velocity was assumed as reference frequency response parameter. Geofoam material (two-component Polyurethane lightweight material) properties were derived from [24–27]

whereas a common sand soil was considered with a Young Modulus of about 300 MPa, Poisson Ratio of 0,35 and Density of 1800 kg/m^3.

Attenuation has been evaluated throughout the frequency domain for a receiver located behind the trench at 5 and 10 m far away from the trench itself. The vibration source is positioned at 10 m far away from the trench. A continuous layout has been considered and two different trenches depth (namely H = 10 and 20 m) have been examined. Results have been summarized in the following figure (Fig. 5).

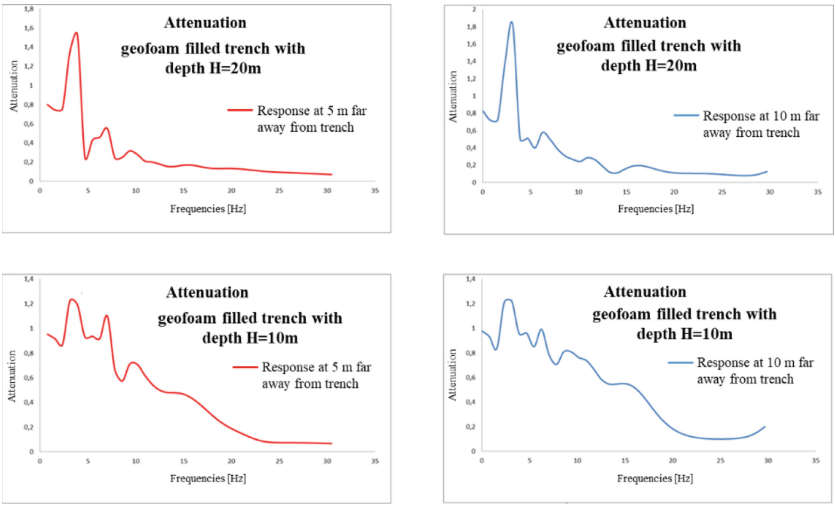


Fig. 5. Influence on attenuation in frequency domain of trenches with different depth and receiver's position behind the trench.

As it can be observed, deeper trench may offer a more effective mitigation of vibration with respect to shallow ones as also reported in scientific literature [17–23]. It is also worth to be noticed that attenuation is not always effective within the investigated frequency range. As a matter of fact, even for trenches filled with geofoam (soft) materials a clear resonance peak can be detected in the 2–3 Hz range thus arising some cautions on the design of this countermeasure as far as the predominant frequency content of the vibration source is concerned.

Another interesting aspect that can be tackled by means of a numerical FEM 3D modelling is the evaluation of vibration mitigation in case of complex geometric trench layout. In this connection, the effectiveness in attenuation has been investigated by comparing the performance provided by a conventional (infinite) trench and variable (depth-dependent) porosity trench that are depicted below (Fig. 6).

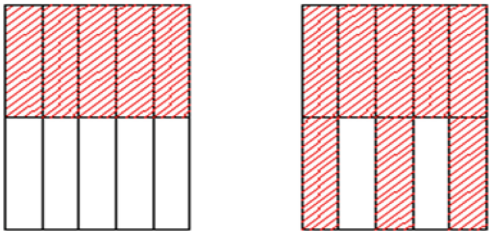


Fig. 6. Schematics of the examined different trench geometric layout. Front view for a conventional trench (on the left) and a variable (depth-dependent) porosity trench (on the right).

In the following figure the attenuation is reported for receivers located at different distance from the trench. As it can be observed for the specific investigated scenario, the performance of variable porosity trench is even somehow better in the first resonance peak only to slightly worsen at higher frequencies thus suggesting that the trench complex layouts may offer more "tailored" solutions apart from trivial economic benefits (Fig. 7).

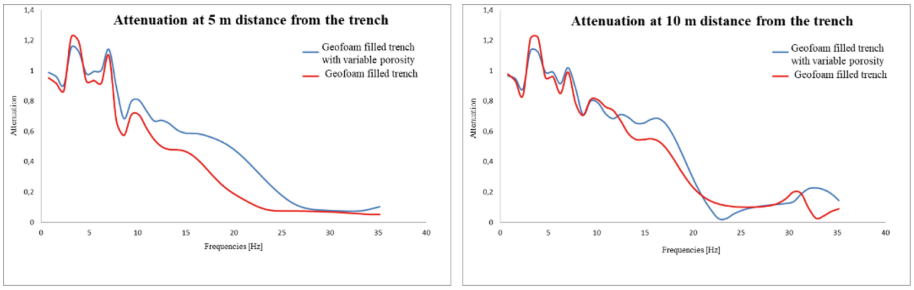


Fig. 7. Performance comparison between conventional geofoam filled trench and variable porosity geofoam filled trench.

Basing on the evaluation of the *Average Attenuation* within a defined frequency range, *Trench Efficiency, TE,* may be defined as:

$$Trench\ Efficiency = 1 - Average\ Attenuation \tag{4}$$

In the following figure the comparison between an infinite and a finite trench is conveniently reported in terms of *Trench Efficiency* for different receiver positions that progressively move away from the vibration source. As it can be easily highlighted, efficiency generally decreases going far away from the trench and from the vibration source. However, 3D modelling seems able to capture the typical "*shadow zone effect*" provided by finite (in terms of plan view layout) trenches with respect to the continuous (infinite) ones (Fig. 8).

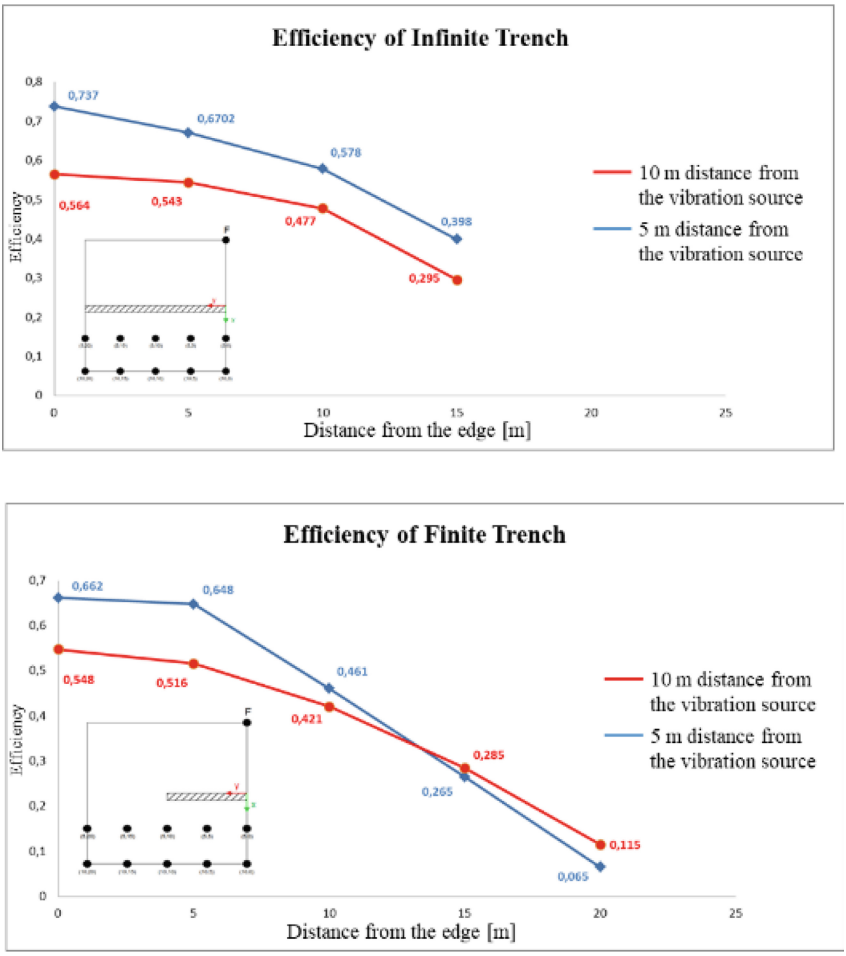


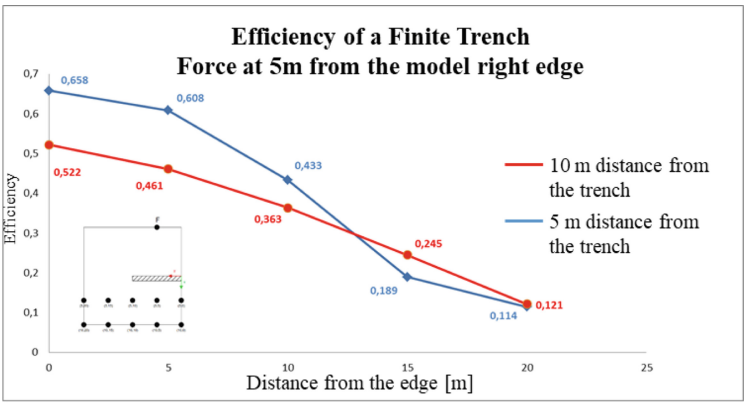
Fig. 8. Trench efficiency comparison between infinite (above) and finite (below) trench. A plan view of the investigated schemes is also reported for sake of clarity.

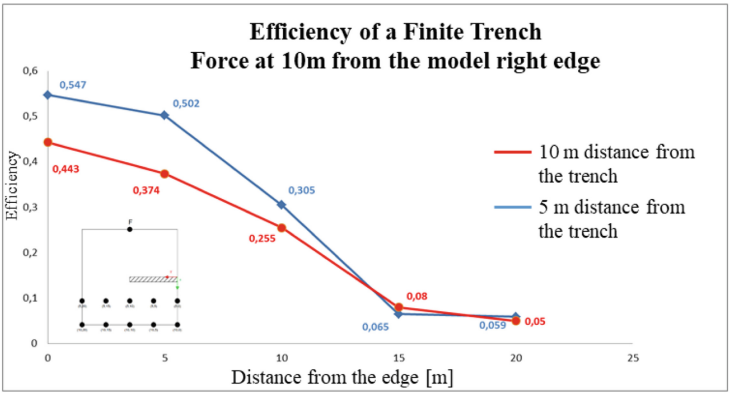
4 Discussions

It seems to be worth to mention that the 3D modelling approach employed may allow a more realistic modelling of the phenomenology related to vehicular traffic induced vibrations.

As a matter of fact, as far as ground-borne vibration induced by vehicular traffic is concerned, it has to be acknowledged that the vibration source is inherently moving with respect to the receiver position.

Furthermore, it has to be highlighted that as far as road traffic vibration is concerned, because of the low vehicle speed compared with relevant vibration wave speed (in such case Rayleigh waves are predominant [6]), the system can be regarded as dynamically





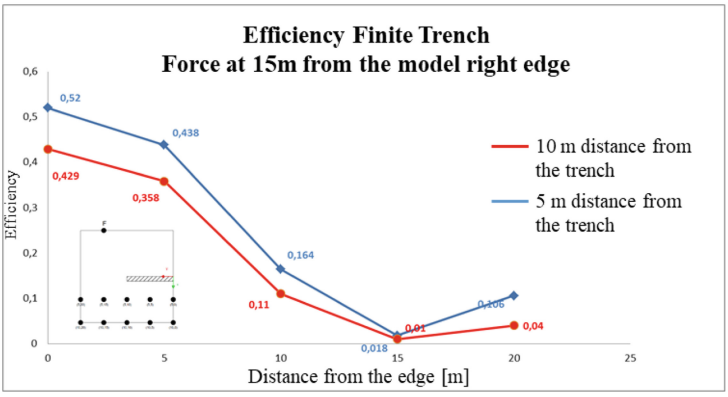


Fig. 9. Trench efficiency comparison of finite trench for different relative vibration source position. A plan view of the investigated schemes is also reported for sake of clarity.

uncoupled and therefore the moving vibration source can be modelled as nearly quasi-static.

It can be therefore relevant to study the performance of a finite trench with respect to different vibration source position. This task can be easily accomplished by making use of a typical hemi-symmetric scheme and of the effect superposition principle because of the linear mechanical behavior of involved materials. Basing on these premises, it has been possible to study the efficiency of finite trenches for different position of vibration source travelling along the road alignment. Results are conveniently depicted in the following figure where again the "*shadow zone effect*" can again be found i.e. the efficiency of the Finite Trench drops when the receiver is directly exposed to the vibration source whereas significantly increased when the receiver point is located just behind the anti-vibrating screen.

These results that seem consistent with those provided by main scientific literature [17–27] may offer an interesting starting point to develop more simplified phenomenological-based predictions tools to evaluate efficiency of specific finite trench in terms of filling material geometrical layouts and on site soil conditions (Fig. 9).

5 Conclusions

In this paper, following a review of scientific literature on ground-borne vibration induced by road traffic, a new 3D numerical model has been developed in order to study the vibration screening effectiveness of several type of trenches layouts filled with geofoam to be employed in an urban environment.

The use of 3D modelling is related to the need of investigating different layouts (such as finite and infinite trenches or trenches with specific and complex geometries) and different relative positions for vibration source and for the receiver that cannot be accurately captured by a 2D modeling approach. Due to the required higher computational effort, a preliminary mesh optimization has been performed. Preliminary results obtained with a sand soil seem to highlight that:

- geofoam filled trenches may offer a valid solution in mitigating traffic vibrations;
- theoretical numerical model should be carefully developed and calibrated in order to help designer in evaluating the effectiveness of specific solutions;
- although deeper trenches are more effective than shallow ones, the attenuation is not uniform within the investigated frequency range due to trench material and soil resonance/impedance phenomena;
- variable depth porosity trenches appear more beneficial at lower frequencies;
- for finite (in plan) trenches, the developed model seems to adequately capture the "*shadow zone effect*" in attenuation for different position receivers behind the trench or by moving vibration sources.

The novelty of the proposed approach may be of interest for future research because of:

- the use of a simple FEM model to simulate the vibration propagation in the near field conditions instead of a hybrid BEM-FEM approach that is not so widespread diffused in the technical community;

- the numerical validation of the FEM model with closed-form analytical solutions that can guarantee a better mathematical reliability of the proposed modeling approach
- the experimental validation of the FEM model with field data collected on different soils and derived from scientific literature;
- the ability to implement complex trench layout that could be designed in a tailoring way for the specific intervention site.

However, additional simulations have to be undertaken in order to highlight the performance with soils other than that specifically examined (both in terms of material properties and in terms of geometrical layout such as *layered* soils). Furthermore, it is worth to observe that an experimental validation with test trials would be beneficial in assessing the effectiveness of such mitigation solutions.

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